Impacts of climate change on methane emissions from wetlands

Drew T. Shindell, Bernadette P. Walter, and Greg Faluvegi

NASA Goddard Institute for Space Studies and Columbia University, New York, New York, USA

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[1] We have included climate-sensitive methane emissions from wetlands within the GISS climate model using a linear parameterization derived from a detailed process model. The geographic distribution of wetlands is also climate–dependent. Doubled CO_2 simulations using this model show an increase in annual average wetland methane emissions from 156 to 277 Tg/yr, a rise of 78%. The bulk of this increase is due to enhanced emissions from existing tropical wetlands. Additionally, high northern latitude wetland areas expand and emissions nearly triple during Northern summer. The global increase represents ~20% of present-day inventories. These large values indicate that the potential response of natural emissions to climate change merit greater study, and should be included in projections of future global warming and tropospheric pollution. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 0322 Atmospheric Composition and Structure: Constituent sources and sinks; 1615 Global Change: Biogeochemical processes (4805); 1890 Hydrology: Wetlands. **Citation:** Shindell, D. T., B. P. Walter, and G. Faluvegi (2004), Impacts of climate change on methane emissions from wetlands, *Geophys. Res. Lett.*, *31*, L21202, doi:10.1029/2004GL021009.

1. Introduction

[2] Methane increases have contributed about 0.7 W/m^2 to global radiative forcing since preindustrial times (0.5 W/m^2 directly, plus an additional 0.2 W/m^2 indirectly via tropospheric ozone and stratospheric water vapor), roughly one-half the forcing from CO_2. This makes it the second most important greenhouse gas forcing [*Hansen et al.*, 2000; *Ramaswamy et al.*, 2001]. Controlling methane emissions could mitigate global warming as much as controlling CO_2 over the next century [*Kheshgi et al.*, 1999], and might be a more practical way to reduce near-term climate forcing, owing to methane's shorter lifetime and the collateral economic benefits of increased methane capture [*Hansen et al.*, 2000]. Projections of future emissions are typically based only on potential changes in anthropogenic emissions. It is possible, however, that natural emissions could also change substantially.

[3] Methane emissions from wetlands are the dominant natural source, contributing around 100–230 Tg/yr [*Hein et al.*, 1997; *Houweling et al.*, 1999; *Matthews*, 2000]. They represent ~20–45% of total emissions (~500 Tg/yr). Thus changes in wetland emissions could significantly impact future methane levels.

[4] Near the end of the last Ice Age methane increased substantially following large temperature increases [*Severinghaus and Brook*, 1999]. Since natural emissions from wetlands dominated preindustrial emissions, this implies a large wetland response to climate anomalies. Models also suggest a large response. One found ±20% emission changes in response to globally uniform temperature variations of ±1 C, and ±8% emission changes in response to globally uniform precipitation variations of ±20% [*Walter et al.*, 2001b]. Other studies include regional modeling [*Christensen and Cox*, 1995] and investigations of wetland emissions at various preindustrial periods [*Houweling et al.*, 2000; *Kaplan*, 2002]. Here we provide first-order estimates of the response of global natural wetland emissions to potential future climate change using a relatively simple emission model within a general circulation model (GCM).

2. Model

[5] A simple wetland distribution model and parameterized methane emissions as a function of climate have been incorporated within the Goddard Institute for Space Studies (GISS) GCM. The emissions module calculates the response to GCM soil temperature and precipitation anomalies using values derived from a detailed process-model run at 1° × 1° (latitude by longitude) that calculates wetland emissions as a function of the water table, soil temperature, and net primary productivity (NPP) [*Walter et al.*, 2001a]. The process model includes transitions between bacterial decomposition under anaerobic or aerobic conditions as the water table varies. That model simulates global wetland emissions in good agreement with results from inverse modeling, and reproduces the seasonality of emissions in comparisons with observations at several sites. The model was driven with meteorological fields from the European Center for Medium-Range Weather Forecasts (ECMWF) for 1982 to 1993 to examine seasonal and interannual variability [*Walter et al.*, 2001b].

[6] Relationships between monthly emissions and monthly mean upper layer soil temperature anomalies and precipitation anomalies averaged over the preceding month (i.e., lagged two weeks to allow for the water table's response time) were calculated from that run using linear regression. Thus correlations between climate anomalies and wetland methane emissions were derived independently across the globe as a function of local (1° × 1°) NPP, amount and quality of the soil substrate for methanogenesis, rooting depth, soil depth, relative pore space, and plant-mediated transport [see *Walter et al.*, 2001a]. These correlations were then included within the GCM averaged over its 4° × 5° grid so that emissions depend upon the climate model's soil temperature and precipitation anomalies, lagged one and two weeks, respectively. Anomalies are calculated with respect to ECMWF values so that emissions are truly tied to the GCM's climate even for the present.

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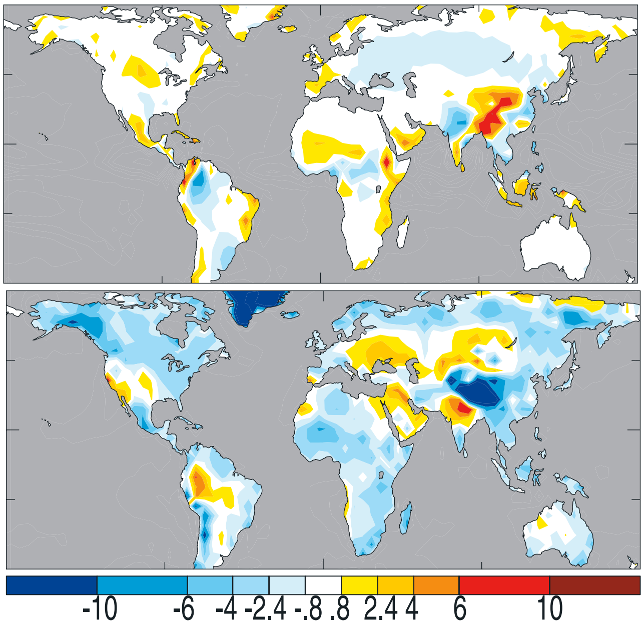

Figure 1. GCM biases relative to climatology [*Legates and Willmott*, 1990; *Xie and Arkin*, 1997] for June–August average precipitation (mm/day, top) and surface temperature (C, bottom).

[7] Methane emissions from wetlands in the GCM thus depend upon the realism of the model's climate. We use the GISS model II' in the configuration used for atmospheric chemistry simulations [*Shindell et al.*, 2003]. This model reproduces observed temperature and precipitation fairly well (Figure 1). JJA precipitation is generally close to observed values in wetland regions, with the largest biases occurring near the Himalayas and Andes. Temperatures biases are greatest in the same regions, but are otherwise fairly small. Other seasons are similarly well simulated.

[8] The wetland distribution is derived using thresholds for parameters that influence methane emissions. A parameter-space search using GCM fields found the optimum threshold values in comparison with the distribution of *Fung et al.* [1991]: maximum standard deviation of topography 205 m, minimum ground temperature −9 C, minimum ground wetness 18% (at vegetation rooting depth), and minimum downward shortwave flux 27 W/m^2. These values are for entire grid boxes, and exclude heavily developed areas of the United States and Europe where human activities dominate wetland distributions. The GCM's hydrology includes standard components such as specified surface runoff direction and lake fill depth, and a soil holding capacity dependent upon specified soil type.

[9] The resulting distribution matched the *Fung et al.* [1991] classification of land boxes as wetlands seasonally as follows: DJF 90.4%, MAM 83.8%, JJA 77.5%, and SON 81.3%. This is quite good given GCM and dataset biases, as well as the difficulty of matching local conditions with large grid boxes (as also noted by *Coe* [1998]). The model underestimates wetland areas in southern South America, especially in DJF, however. This stems from a negative bias in model precipitation, which falls too much on the western side of the Andes.

[10] GCM simulations were run including this distribution model. Locations with emissions in the *Fung et al.* [1991] dataset were given that base emission, which was then modified by the emissions model described above. Locations determined to contain wetlands which were not in the dataset were given the zonal mean emission value. To test the importance of this infilling, we ran a simulation with infilling instead based on the average over squares of the nearest 8 neighbors, the next ring of 14, etc., expanding until a non-zero emissions was determined. Though seasonality in the emissions was slightly weaker, the annual average emission sensitivity to climate change was identical between the two methods.

[11] Global annual average emissions are poorly known at present, with a recent top-down (using atmospheric amounts to derive emissions) study giving 232 ± 27 Tg/yr [*Hein et al.*, 1997], while a recent bottom-up (using small scale emission measurements extrapolated to the global scale) study gave 145 ± 41 Tg/yr [*Houweling et al.*, 1999]. We therefore compare the simulated emissions using the distribution and emission anomaly models with *Fung et al.* [1991] scaled to match the annual average (Table 1). The model captures the seasonality of methane emissions, though the amplitude is too weak. This is primarily due to emissions being ∼20% too large during DJF.

3. Results

[12] Wetland emissions were calculated in the GCM for doubled CO_2, a standard benchmark for climate studies. Ocean conditions were taken from a previous doubled CO_2 run with a global mean annual average surface temperature increase of 3.4 C. Methane emissions are dramatically enhanced in a warmer, wetter climate; more than doubling during JJA (Table 1). The annual average increase of 121 Tg/yr (78%) represents ∼20% of present day total emissions.

[13] Most increases are driven by both warmer temperatures and enhanced precipitation. Central African emissions show a stronger dependence upon temperature, as JJA precipitation decreases at some locations which nevertheless produce enhanced emissions. Emissions from high northern latitudes increase sharply during JJA over broad areas of Canada, Russia and Finland (Figure 2). Annually averaged, however, the tropics contribute nearly two-thirds of the total increase (Table 2). Most tropical increases come from Africa, which shows a sizeable response in every season (Figure 2). South American emissions show substantial increases only in MAM. Note that Indonesian emissions are underestimated, owing to a cold bias there, though they

Table 1. Methane Emissions From Wetlands (Tg)

Season	Prescribed Emissions[a]	Present-Day Run[b]	2 × CO_2 Run[b] (% Increase)
DJF	28	34	52 (53%)
MAM	39	39	72 (85%)
JJA	45	43	88 (105%)
SON	44	40	64 (60%)
ANN	156	156	277 (78%)

[a]*Fung et al.* [1991] normalized to 156 Tg/yr for comparison with the modeled emissions.
[b]Simulation with climate-responsive emissions and distributions.

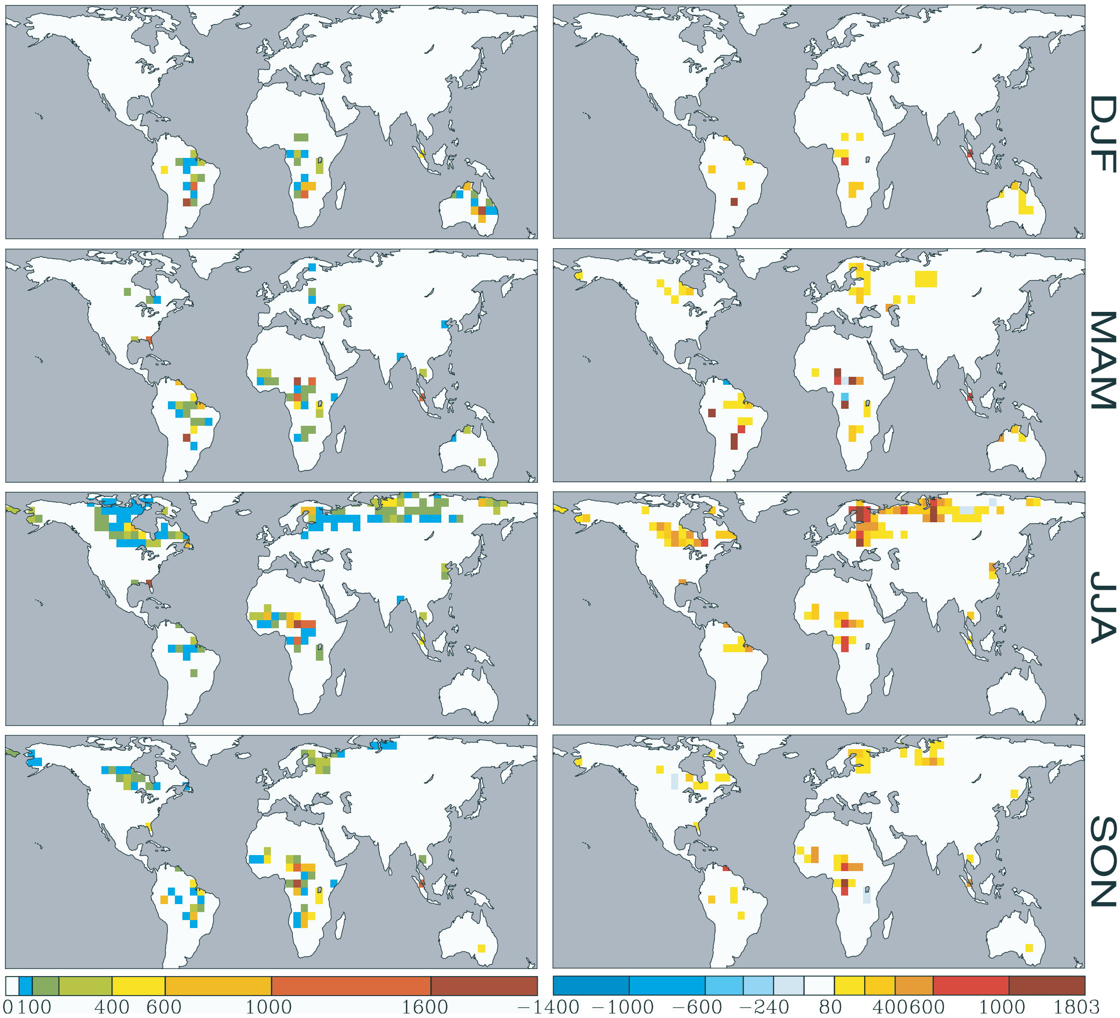

Figure 2. Seasonal methane emissions (1E-12 kg/s/m^2) from wetlands in the simulations with climate-responsive emissions and distributions for the present (left column) and the difference between the present and doubled carbon dioxide (right column).

are relatively small [*Fung et al.*, 1991]. Few areas show reduced emissions.

[14] An additional simulation with climate-responsive emissions but a fixed distribution showed an emission increase of 99 Tg/yr. Thus the increases result primarily from enhancement of existing wetlands rather than creation of new wetlands. However, 11 Tg (37%) of the increase in high northern latitude JJA emissions are attributable to the expansion of wetlands (Table 2). Increased area also contributes 5 Tg (19%) of the tropical MAM emissions enhancement (Table 2).

[15] Temperatures at Northern high latitudes warmed by about 3–5 degrees in our model, while MAM and JJA precipitation increased by around 0.4–0.8 mm/day over northern Eurasia. This led to a doubling of annual average emissions in the case with a fixed wetland distribution, and to a 175% increase in emissions in the responsive distribution case (Table 2). Such a large sensitivity is consistent with both an enhanced flux per unit area under warmer conditions and a precipitation-induced expansion of the depth of waterlogged soils with anaerobic emissions [see, e.g., *Christensen and Cox*, 1995, Figure 1].

[16] These results are in accord with estimates that a 3–5 degree temperature increase would more than double boreal emissions [*Frolking*, 1993], and that a ~5 degree warming triples mid-summer northern Alaskan emissions

Table 2. Tropical (32 S to 32 N) and Northern (32 N to 90 N) Methane Emissions and Increases (Tg) for Doubled CO_2

Season	Current, Tropics	Current, Northern	Increase, Responsive Emissions and Area, Tropics	Increase, Responsive Emissions and Area, Northern	Increase, Responsive Emissions Only, Tropics	Increase, Responsive Emissions Only, Northern
DJF	36	0.6	18	0.2	18	0.1
MAM	37	2	27	6	22	4
JJA	25	17	15	30	15	19
SON	35	5	18	6	16	5
ANN	133	24	78	42	71	28

[*Livingston and Morrissey*, 1991]. Another study showed a comparable increase in high latitude emissions in response to warming, but a large reduction should the water table drop [*Roulet et al.*, 1992]. That model's results appear comparable to ours, since our simulations showed increased precipitation at high latitudes along with warmer temperature and therefore an increased emission. Projected precipitation, however, is significantly more uncertain than temperature.

[17] The most comparable study used a simple emission model and the single column version of the Hadley Centre climate model to estimate the response of Arctic emissions to doubled CO_2 [*Christensen and Cox*, 1995]. Their emission model was similar to ours, including dependence on soil temperature, soil moisture and thaw depth. The latter is implicitly included in our regression response coefficients at high Northern latitudes. In their doubled CO_2 case, temperature increased by 4 C and precipitation by 0.3 mm/day (the latter slightly less than in our model), causing methane emissions to increase from 17.1 to 26.6 Tg/yr (+56%). Our Northern high latitude emissions in the simulations with fixed distribution, the most comparable to their setup, increased from 24 to 52 Tg/yr (Table 2). Thus there is qualitative agreement in the existing studies that climate change can greatly enhance methane emissions from wetlands, but the magnitude is fairly uncertain, even at regional scales.

4. Discussion

[18] The process model responses were based upon interannual variability during the 1980s and 1990s. Climate conditions for grid-boxes containing wetlands were outside that local variability a bit less than one-third of the time in the doubled CO_2 run. This will have little impact if the response is roughly linear. Of course, our linear parameterization cannot capture any non-linearities. Additionally, the GCM resolution is coarse relative to the scale at which emissions vary. Thus our methodology leaves substantial room for improvement, though we believe it is likely to give a plausible first-order estimate of the emission response to CO_2 doubling. In the future, we intend to compare the use of linearized responses derived from a detailed process model with the approach of using a simplified process model such as *Kaplan* [2002] within the GCM. By coupling emissions to the GCM's vegetation, this would allow distributions to be affected by changes in vegetation (e.g., from CO_2 fertilization) or in the supply of organic substrates or nutrients, especially N and P, which could be limiting factors in methane production [*Maltby and Proctor*, 1996]. Simulation of precipitation is likely to remain a major source of uncertainty, however, especially at small spatial scales, as is our ability to model some aspects of the water table such as formation of oxic layers in deeper waters or wetland area changes in floodplains where topographic gradients are extremely small.

[19] Degradation and collapse of peats, which could affect future high northern latitude emissions [*Liblick et al.*, 1997], are also not accounted for. Additionally, future methane emissions from wetlands may be strongly affected by human drainage and cultivation activities. This has not been included, as we cannot predict future economic and public policy trends that would drive such changes. Thus many uncertainties remain in modeling climate-responsive methane emissions.

[20] Enhanced wetland methane emissions of 121 Tg/yr would increase the atmospheric burden by ~1000 Tg, about 430 ppbv, using the current methane residence time of ~8.4 years. Future methane abundance, however, will also be influenced by changes in methane's oxidation rate. This will be affected by pollutant and natural hydrocarbon emissions, changes in tropospheric water vapor due to climate change, and methane's feedback upon its own lifetime. Future work should calculation the global methane cycle addressing this issue using coupled chemistry-biosphere-climate models.

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G. Faluvegi, D. T. Shindell, and B. P. Walter, NASA Goddard Institute for Space Studies and Columbia University, 2880 Broadway, New York, NY 10025, USA. (dshindell@giss.nasa.gov)